

Measurement of the Strong Phase in $D^0 \rightarrow K^+\pi^-$ Using Quantum Correlations

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We exploit the quantum coherence between pair-produced D^0 and \bar{D}^0 in $\psi(3770)$ decays to study charm mixing and to make a first measurement of the relative strong phase δ between $D^0 \rightarrow K^+\pi^-$ and $\bar{D}^0 \rightarrow K^+\pi^-$. Using 281 pb^{-1} of e^+e^- collision data collected with the CLEO-c detector at $E_{\text{cm}} = 3.77 \text{ GeV}$, as well as branching fraction input from other experiments, we make a preliminary determination of $\cos \delta = 1.03 \pm 0.19 \pm 0.08$, where the uncertainties are statistical and systematic, respectively. By further including other external mixing parameter measurements, we obtain an alternate measurement of $\cos \delta = 0.93 \pm 0.32 \pm 0.04$, where the systematic uncertainty from assuming $x \sin \delta = 0$ has not been included.

1. Introduction

Recent measurements of D^0 - \bar{D}^0 mixing parameters [1, 2, 3, 4] highlight the need for information on the relative phase between the Cabibbo favored decay $D^0 \rightarrow K^-\pi^+$ and the doubly Cabibbo suppressed decay $\bar{D}^0 \rightarrow K^-\pi^+$. Here, we present a measurement that takes advantage of the correlated production of D^0 and \bar{D}^0 mesons in e^+e^- collisions. If there are no accompanying particles, the $D^0\bar{D}^0$ pair is in a quantum-coherent $C = -1$ state. Because the initial state (the virtual photon) has $J^{PC} = 1^{--}$, there follows a set of selection rules for the decays of the D^0 and \bar{D}^0 [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. For example, both D^0 and \bar{D}^0 cannot decay to CP eigenstates with the same eigenvalue. On the other hand, decays to CP eigenstates of opposite eigenvalue are enhanced by a factor of two. More generally, final states that can be reached by both D^0 and \bar{D}^0 (such as $K^-\pi^+$) are subject to similar interference effects. As a result, the effective D^0 branching fractions in this $D^0\bar{D}^0$ system differ from those measured in isolated D^0 mesons. Moreover, using time-independent rate measurements, it becomes possible to probe D^0 - \bar{D}^0 mixing as well as the relative strong phases between D^0 and \bar{D}^0 decay amplitudes to any given final state.

In the Standard Model, D^0 - \bar{D}^0 mixing is suppressed both by the GIM mechanism and by CKM matrix elements, although sizeable mixing could arise from new physics [14]. Charm mixing is conventionally described by two small dimensionless parameters:

$$x = 2 \frac{M_2 - M_1}{\Gamma_2 + \Gamma_1} \quad (1)$$

$$y = \frac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1}, \quad (2)$$

where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths, respectively, of the neutral D meson CP eigenstates, D_1 (CP -odd) and D_2 (CP -even), which are defined

as follows:

$$|D_1\rangle \equiv \frac{|D^0\rangle + |\bar{D}^0\rangle}{\sqrt{2}} \quad (3)$$

$$|D_2\rangle \equiv \frac{|D^0\rangle - |\bar{D}^0\rangle}{\sqrt{2}}, \quad (4)$$

assuming CP conservation. The mixing probability is then denoted by $R_M \equiv (x^2 + y^2)/2$, and the width of the D^0 and \bar{D}^0 flavor eigenstates is $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$.

Many previous searches for charm mixing have focused on D^0 decay times. Direct measurements of y come from comparing lifetimes in $D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$ decay to that in $D^0 \rightarrow K^-\pi^+$. An indirect measure of y is provided by the “wrong-sign” process $D^0 \rightarrow K^+\pi^-$, where interference between the doubly-Cabibbo-suppressed (DCS) amplitude and the mixing amplitude manifests itself in the apparent D^0 lifetime. These analyses are sensitive to $y' \equiv y \cos \delta - x \sin \delta$, where $-\delta$ is the phase of the amplitude ratio $\langle K^+\pi^- | D^0 \rangle / \langle K^+\pi^- | \bar{D}^0 \rangle$. Below, we also denote the magnitude of this ratio by r , which is measured to be approximately 0.06. Because δ has not previously been measured, the separate determinations of y and y' above have not been directly comparable.

In this note, we present an implementation of the method described in Ref. [16] for measuring y and $\cos \delta$ using quantum correlations at the $\psi(3770)$ resonance. Our experimental technique is an extension of the double tagging method previously used to determine absolute hadronic D -meson branching fractions at CLEO-c [17]. This method combines yields of fully-reconstructed single tags (ST), which are individually reconstructed D^0 or \bar{D}^0 candidates, with yields of double tags (DT), which are events where both D^0 and \bar{D}^0 are reconstructed, to give absolute branching fractions without needing to know the luminosity or $D^0\bar{D}^0$ production cross section. Given a set of input yields, efficiencies, and background estimates, a least-squares fitter [18] extracts the number of $D^0\bar{D}^0$ pairs produced (\mathcal{N}) and the branching fractions (\mathcal{B}) of the reconstructed D^0 final states, while accounting for all statistical and systematic uncertain-

ties and their correlations. We employ a modified version of this fitter that also determines y , x^2 , r^2 , and $r \cos \delta$ using the following categories of reconstructed final states: $D \rightarrow K^\mp \pi^\pm$, CP -even (S_+) and CP -odd (S_-) eigenstates, and semileptonic decays (e^\pm). For optimal precision on δ , we also incorporate measurements of branching fractions and mixing parameters from other CLEO-c analyses or from external sources. CP violation in D and K decays are negligible second order effects that we ignore.

2. Formalism

To first order in x and y , the C -odd width $\Gamma_{D^0 \bar{D}^0}(i, j)$ for $D^0 \bar{D}^0$ decay to final state i/j follows from the anti-symmetric amplitude \mathcal{M}_{ij} :

$$\begin{aligned} \Gamma_{D^0 \bar{D}^0}(i, j) &\propto \mathcal{M}_{ij}^2 = |A_i \bar{A}_j - \bar{A}_i A_j|^2 \\ &= |\langle i|D_2\rangle\langle j|D_1\rangle - \langle i|D_1\rangle\langle j|D_2\rangle|^2, \end{aligned} \quad (5)$$

where $A_i \equiv \langle i|D^0\rangle$, $\bar{A}_i \equiv \langle i|\bar{D}^0\rangle$. The total width, $\Gamma_{D^0 \bar{D}^0}$, is the same as for uncorrelated decay, as are ST rates. However, unlike the case of uncorrelated $D^0 \bar{D}^0$, we can consider the C -odd $D^0 \bar{D}^0$ system as a $D_1 D_2$ pair. If only flavored final states are considered, as in Ref. [17], then the effects of quantum correlations are negligible. In this analysis, we also include CP eigenstates, which brings additional sensitivity to y and δ , as demonstrated below.

Quantum-correlated semileptonic rates probe y because the decay width does not depend on the CP eigenvalue of the parent D meson, as this weak decay is only sensitive to flavor content. However, the total width of the parent meson does depend on its CP eigenvalue: $\Gamma_{1,2} = \Gamma(1 \mp y)$, so the semileptonic branching fraction for D_1 or D_2 is modified by $1 \pm y$. If we reconstruct a semileptonic decay in the same event as a $D_2 \rightarrow S_+$ decay, then the semileptonic D must be a D_1 . Therefore, the effective quantum-correlated $D^0 \bar{D}^0$ branching fractions (\mathcal{F}^{cor}) for CP -tagged semileptonic final states depend on y :

$$\mathcal{F}_{S_\pm/\ell}^{\text{cor}} \approx 2\mathcal{B}_{S_\pm}\mathcal{B}_\ell(1 \pm y). \quad (6)$$

Combined with estimates of \mathcal{B}_ℓ and \mathcal{B}_{S_\pm} from ST yields, external sources, and flavor-tagged semileptonic yields, this equation allows y to be determined.

Similarly, if we reconstruct a $D \rightarrow K^- \pi^+$ decay in the same event as a $D_2 \rightarrow S_+$, then we know the $K^- \pi^+$ was produced from a D_1 . The effective branching fraction for this DT process is therefore

$$\begin{aligned} \mathcal{F}_{S_+/K\pi}^{\text{cor}} &= |\langle S_+|D_2\rangle\langle K^- \pi^+|D_1\rangle|^2 \\ &= A_{S_+}^2 |A_{K^- \pi^+} + \bar{A}_{K^- \pi^+}|^2 \\ &= A_{S_+}^2 A_{K^- \pi^+}^2 |1 + r e^{-i\delta}|^2 \\ &\approx \mathcal{B}_{S_+}\mathcal{B}_{K\pi}(1 + R_{\text{WS}} + 2r \cos \delta + y), \end{aligned} \quad (7)$$

where $R_{\text{WS}} \equiv \Gamma(\bar{D}^0 \rightarrow K^- \pi^+)/\Gamma(D^0 \rightarrow K^- \pi^+) = r^2 + ry' + R_{\text{M}}$, and we have used $\mathcal{B}_{S_\pm} \propto A_{S_\pm}^2(1 \mp y)$ and $\mathcal{B}_{K\pi} \propto A_{K^- \pi^+}^2(1 + ry \cos \delta + rx \sin \delta)$. In an analogous fashion, we find $\mathcal{F}_{S_-/K^- \pi^+}^{\text{cor}} \approx \mathcal{B}_{S_-}\mathcal{B}_{K\pi}(1 + R_{\text{WS}} - 2r \cos \delta - y)$. When combined with knowledge of \mathcal{B}_{S_+} , y , and r , the asymmetry between these two DT yields gives $\cos \delta$. In the absence of quantum correlations, the effective branching fractions above would be $\mathcal{B}_{S_\pm}\mathcal{B}_{K\pi}(1 + R_{\text{WS}})$.

More concretely, we evaluate Eq. 5 with the above definitions of r and δ to produce the expressions in Table I. In doing so, we use the fact that inclusive ST rates are given by the incoherent branching fractions since each event contains one D^0 and one \bar{D}^0 . Comparison of \mathcal{F}^{cor} with the uncorrelated effective branching fractions, \mathcal{F}^{unc} , also given in Table I, allows us to extract r^2 , $r \cos \delta$, y , and x^2 . Information on \mathcal{B}_i is obtained from ST yields at the $\psi(3770)$ and from external measurements using incoherently-produced D^0 mesons. These two estimates of \mathcal{B}_i are averaged by the fitter to obtain \mathcal{F}^{unc} .

Table I Correlated and uncorrelated effective $D^0 \bar{D}^0$ branching fractions, \mathcal{F}^{cor} and \mathcal{F}^{unc} , to leading order in x , y and r^2 , divided by \mathcal{B}_i for ST modes i (first section) and $\mathcal{B}_i \mathcal{B}_j$ for DT modes i/j (second section). Charge conjugate modes are implied.

Mode	C -odd	Uncorr.
$K^- \pi^+$	$1 + R_{\text{WS}}$	$1 + R_{\text{WS}}$
S_+	2	2
S_-	2	2
$K^- \pi^+ / K^- \pi^+$	R_{M}	R_{WS}
$K^- \pi^+ / K^+ \pi^-$	$(1 + R_{\text{WS}})^2 - 4r \cos \delta (r \cos \delta + y)$	$1 + R_{\text{WS}}^2$
$K^- \pi^+ / S_+$	$1 + R_{\text{WS}} + 2r \cos \delta + y$	$1 + R_{\text{WS}}$
$K^- \pi^+ / S_-$	$1 + R_{\text{WS}} - 2r \cos \delta - y$	$1 + R_{\text{WS}}$
$K^- \pi^+ / e^-$	$1 - ry \cos \delta - rx \sin \delta$	1
S_+ / S_+	0	1
S_- / S_-	0	1
S_+ / S_-	4	2
S_+ / e^-	$1 + y$	1
S_- / e^-	$1 - y$	1

3. Fit Inputs

We analyze 281 pb^{-1} of e^+e^- collision data produced by the Cornell Electron Storage Ring (CESR) at $E_{\text{cm}} = 3.77$ GeV and collected with the CLEO-c detector, which is described in detail elsewhere [19]. We reconstruct the D^0 and \bar{D}^0 final states listed in Table II, with $\pi^0/\eta \rightarrow \gamma\gamma$, $\omega \rightarrow \pi^+\pi^-\pi^0$, and $K_S^0 \rightarrow \pi^+\pi^-$. Signal and background efficiencies, as well as crossfeed probabilities among signal modes, are

determined from simulated events that are processed in a fashion similar to data.

Table II D final states reconstructed in this analysis.

Type	Final States
Flavored	$K^-\pi^+, K^+\pi^-$
S_+	$K^+K^-, \pi^+\pi^-, K_S^0\pi^0\pi^0, K_L^0\pi^0$
S_-	$K_S^0\pi^0, K_S^0\eta, K_S^0\omega$
e^\pm	Inclusive $Xe^+\nu, Xe^-\bar{\nu}$

Hadronic final states without K_L^0 mesons are fully reconstructed via two kinematic variables: the beam-constrained candidate mass, $Mc^2 \equiv \sqrt{E_0^2 - \mathbf{p}_D^2 c^2}$, where \mathbf{p}_D is the D^0 candidate momentum and E_0 is the beam energy, and $\Delta E \equiv E_D - E_0$, where E_D is the sum of the D^0 candidate daughter energies. We extract ST and DT yields from M distributions using unbinned maximum likelihood fits (ST) or by counting candidates in signal and sideband regions (DT).

Because most K_L^0 mesons and neutrinos produced at CLEO-c are not detected, we only reconstruct modes with these particles in DTs, by demanding that the other D in the event be fully reconstructed. Ref. [20] describes the missing mass technique used to identify $K_L^0\pi^0$ candidates. For semileptonic decays, we use inclusive, partial reconstruction to max-

Table III ST and DT yields, efficiencies, and their statistical uncertainties. For DT yields, we sum groups of modes and provide an average efficiency for each group; the number of modes in each group is given in parentheses. Modes with asterisks are not included in the standard and extended fits.

Mode	Yield	Efficiency (%)
$K^-\pi^+$	25400 ± 200	64.70 ± 0.04
$K^+\pi^-$	25800 ± 200	65.62 ± 0.04
K^+K^-	4740 ± 70	57.25 ± 0.09
$\pi^+\pi^-$	2100 ± 60	72.92 ± 0.13
$K_S^0\pi^0\pi^0$	2440 ± 70	12.50 ± 0.06
$K_S^0\pi^0$	7520 ± 90	29.73 ± 0.05
$K_S^0\eta$	1050 ± 40	10.34 ± 0.06
$K_S^0\omega$	3240 ± 60	12.48 ± 0.04
$K^\mp\pi^\pm/K^\mp\pi^\pm$ (2)	4 ± 2	40.2 ± 2.4
$K^-\pi^+/K^+\pi^-$ (1)	600 ± 25	41.1 ± 0.2
$K^\mp\pi^\pm/S_+$ (8)	605 ± 25	26.1 ± 0.1
$K^\mp\pi^\pm/S_-$ (6)	243 ± 16	12.3 ± 0.1
$K^\mp\pi^\pm/e^\mp$ (2)	2346 ± 65	45.6 ± 0.1
S_+/S_+ (9*)	10 ± 6	12.5 ± 0.6
S_-/S_- (6*)	2 ± 2	3.9 ± 0.2
S_+/S_- (12)	242 ± 16	7.7 ± 0.1
S_+/e^\mp (6)	406 ± 44	22.2 ± 0.1
S_-/e^\mp (6)	538 ± 40	13.8 ± 0.1

imize efficiency, demanding that only the electron be identified with a multivariate discriminant [21] that combines measurements from the tracking chambers, the electromagnetic calorimeter, and the ring-imaging Čerenkov counter.

Table III gives yields and efficiencies for 8 ST modes and 58 DT modes, where the DT modes have been grouped into categories. Fifteen of the DT modes are forbidden by CP conservation and are not included in the standard fit. In general, crossfeed among signal modes and backgrounds from other D decays are smaller than 1%. Modes with $K_S^0\pi^0\pi^0$ have approximately 3% background, and yields for $K^\mp\pi^\pm/K^\mp\pi^\pm$ and S_\pm/S_\pm are consistent with being entirely from background.

External inputs to the fit include measurements of R_M , R_{WS} , $\mathcal{B}_{K^-\pi^+}$, and \mathcal{B}_{S_\pm} , as well as an independent $\mathcal{B}_{K_L^0\pi^0}$ from CLEO-c, as shown in Table IV. The external R_{WS} is required to constrain r^2 , and thus, to determine $\cos\delta$ from $r\cos\delta$. We also use the external mixing parameter measurements shown in Table V. The fit incorporates the full covariance matrix for these inputs, accounting for statistical overlap with the yields in this analysis. Covariance matrices for the fits in Ref. [27] have been provided by the CLEO, Belle, and BABAR collaborations.

Table IV Averages of external measurements used in the standard fit. Charge-averaged D^0 branching fractions are denoted by final state.

Parameter	Average
R_{WS}	0.00409 ± 0.00022 [22]
R_M	0.00017 ± 0.00039 [23]
$K^-\pi^+$	0.0381 ± 0.0009 [24]
$K^-K^+/K^-\pi^+$	0.1010 ± 0.0016 [25]
$\pi^-\pi^+/K^-\pi^+$	0.0359 ± 0.0005 [25]
$K_L^0\pi^0$	0.0097 ± 0.0003 [20]
$K_S^0\pi^0$	0.0115 ± 0.0012 [24]
$K_S^0\eta$	0.00380 ± 0.00060 [24]
$K_S^0\omega$	0.0130 ± 0.0030 [24]

Table V Averages of external measurements used in the standard and extended fits.

Parameter	Average
y	0.00662 ± 0.00211 [2, 25, 26]
x	0.00811 ± 0.00334 [26]
r^2	0.00339 ± 0.00012 [27]
y'	0.0034 ± 0.0030 [27]
x'^2	0.00006 ± 0.00018 [27]

Systematic uncertainties associated with efficiencies for reconstructing tracks, K_S^0 decays, π^0 decays, and

for hadron identification are assigned as described in Ref. [29]. Other sources of efficiency uncertainty include: ΔE requirements (0.5–5.5%), η reconstruction (4.0%), electron identification (1.0%), modeling of particle multiplicity and detector noise (0.1–1.3%), simulation of initial and final state radiation (0.5–1.2%), and modeling of resonant substructure in $K_S^0\pi^0\pi^0$ (0.7%). We also include additive uncertainties of 0.0–0.9% to account for variations of yields with fit function.

These systematic uncertainties are included directly in the covariance matrix given to the fitter, which propagates them to the fit parameters. The other fit inputs determined in this analysis are ST and DT yields and efficiencies, crossfeed probabilities, background branching fractions and efficiencies, and statistical uncertainties on all of these measurements. Quantum correlations between signal and background modes are accounted for using assumed values of amplitude ratios and strong phases that are systematically varied and found to have negligible effect. We validated our analysis technique in a simulated C -odd $D^0\bar{D}^0$ sample 15 times the size of our data sample.

4. Preliminary Fit Results

Our standard fit excludes the 15 same- CP DT modes and includes the measurements in Table IV but not Table V. In this fit, there is not enough information to reliably determine $x\sin\delta$, so we fix it to zero, and the associated systematic uncertainty is negligible. We obtain a first measurement of $\cos\delta = 1.03 \pm 0.19 \pm 0.08$, consistent with being at the boundary of the physical region. The fit results for y , r^2 , x^2 , and branching fractions are consistent with previous measurements.

The likelihood curve for $\cos\delta$, computed as $\mathcal{L} = e^{-(x^2 - x_{\min}^2)/2}$ and shown in Figure 1, is slightly non-Gaussian. For values of $|\cos\delta| < 1$, we also show \mathcal{L} as a function of $|\sin\delta|$. We integrate these curves within the physical region to obtain 95% confidence level limits of $\cos\delta > 0.54$ and $|\sin\delta| < 0.72$.

We also perform an extended fit that includes the previous measurements of y and y' in Table V, in addition to all the inputs to the standard fit above. In this fit, we find $\cos\delta = 0.93 \pm 0.32 \pm 0.04$. The systematic uncertainty does not include the contribution from assuming $x\sin\delta = 0$, which is still under study. From the corresponding likelihood functions shown in Figure 1, we determine 95% confidence level limits of $\cos\delta > 0.38$ and $|\sin\delta| < 0.84$.

The $\cos\delta$ uncertainty in the extended fit is larger than in the standard fit because of a non-linear effect. Most of the information on r^2 (and therefore on r) is provided by R_{WS} . Because R_{WS} also depends on $y \cdot r \cos\delta$, the sign of the correlation between r^2 and $r \cos\delta$ is given by the sign of y . In the standard fit,

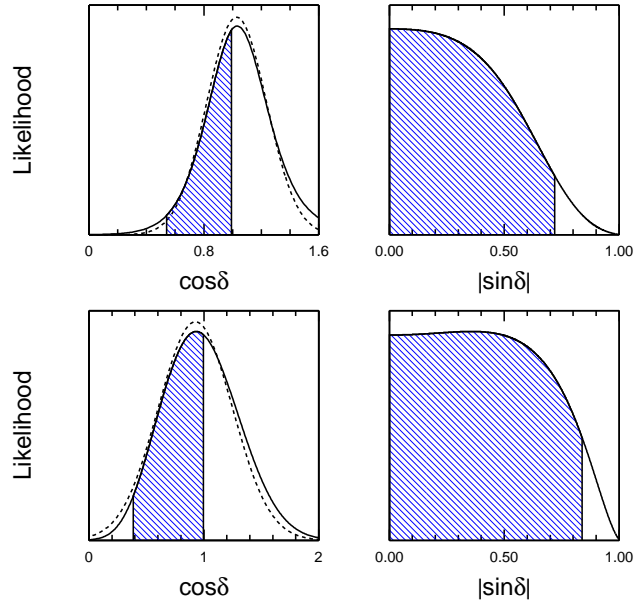


Figure 1: Standard (top) and extended (bottom) fit likelihood functions for $\cos\delta$ and $|\sin\delta|$, including both statistical and systematic uncertainties, excluding the uncertainty from assuming $x\sin\delta = 0$. The dashed curve shows the Gaussian likelihood corresponding to the standard fit result. The hatched regions contain 95% of the areas in the physical regions.

y attains a more negative central value than in the extended fit, where y is constrained to the precise external measurements. Hence, the uncertainty on $\cos\delta$ becomes inflated in the extended fit.

By observing the change in $1/\sigma_{\cos\delta}^2$ as each fit input is removed, we identify the major contributors of information about $\cos\delta$ to be the $K\pi/S_{\pm}$ DT yields and the ST yields. We also find that no single input or group of inputs exerts a pull larger than three standard deviations on $\cos\delta$ or y . Moreover, removing all external inputs gives branching fractions consistent with those in Table IV.

We also allow for a C -even $D^0\bar{D}^0$ admixture in the initial state, which is expected to be $\mathcal{O}(10^{-8})$ [30], by including the 15 S_{\pm}/S_{\pm} DT yields in the fit. These modes limit the C -even component, which can modify the other yields as described in Ref. [16]. In both the standard and extended fits, we find a C -even fraction consistent with zero with an uncertainty of 2.4%, and neither the fitted $\cos\delta$ values nor their uncertainties are shifted noticeably from the results quoted above.

5. Summary

Using 281 pb^{-1} of e^+e^- collisions produced at the $\psi(3770)$, we make a preliminary first determination of the strong phase δ , with $\cos\delta = 1.03 \pm 0.19 \pm 0.08$. By

further including external mixing parameter measurements in our analysis, we obtain an alternate measurement of $\cos \delta = 0.93 \pm 0.32 \pm 0.04$, where the systematic uncertainty from assuming $x \sin \delta = 0$ has not been included. Knowledge of δ allows independent measurements of y and y' to be combined, thereby improving our overall knowledge of charm mixing parameters.

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